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Transform-limited 1.4 ps optical pulses from a monolithic colliding-pulse mode-locked quantum well laser

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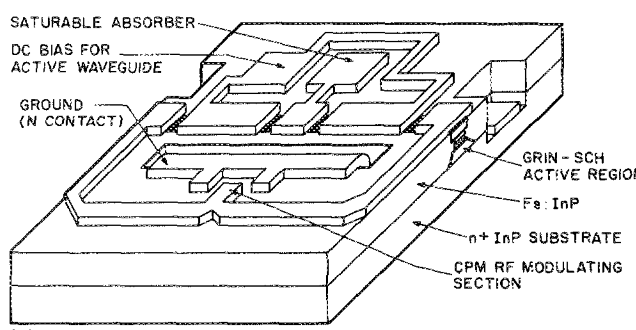
We report the generation of short optical pulses from novel monolithic colliding-pulse mode-locked quantum well lasers. Transform-limited pulses with durations of 1.4 ps at a repetition rate of 32.6 GHz have been achieved, with nearly 100% intensity modulation depth and a peak optical power of 10 mW. This is the shortest transform-limited pulse directly generated from monolithic mode-locked lasers (time-bandwidth product = 0.3).

Significant progress in generating ultrashort optic pulses has been achieved since the development of colliding-pulse mode-locking (CPM) technique.[1,2] High bit rate time-division multiplexed communication systems require compact and externally synchronized active mode-locked semiconductor laser sources.[3–8] Though short pulses have been obtained in mode-locked semiconductor lasers using external cavities, the bulk optics of the cavity causes excess loss and poor stability. Furthermore, the nonperfectly antireflection-coated surface in the cavity often produces uncontrolled multiple pulses in a single cycle. Recently, monolithic mode-locked semiconductor lasers have produced short pulses with a long passive cavity[7] or with hybrid mode-locking technique.[8]

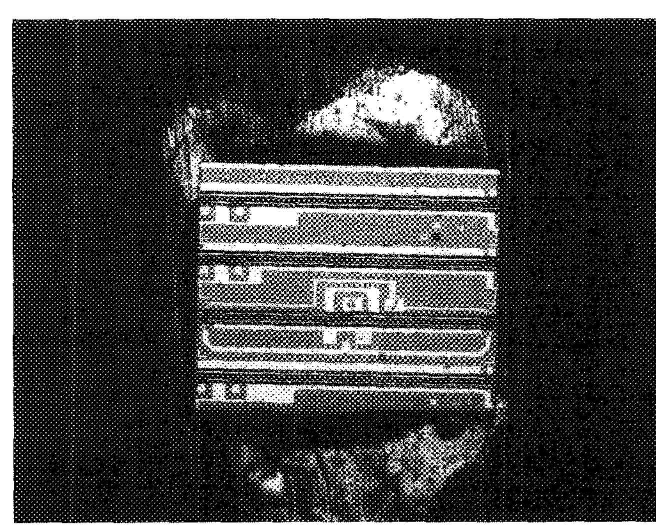
Quantum well structures are unique for integrated active mode-locked lasers. The recently observed fast exciton-relaxation processes in quantum wells[9] substantially improved the pulse shaping in the passive mode-locking experiments using multiquantum wells as an external saturable absorber and a GaAs double-heterostructure (DH) laser.[10,11] Other properties of quantum well lasers, such as high differential-gain coefficient, low internal loss, and low dispersion,[12,13] also significantly improve the performance of integrated modulators and active waveguides. In this letter, we monolithicly incorporate the CPM techniques in an actively mode-locked quantum well laser to generate short pulses at high repetition rate useful for future tera-bit long-wavelength optical communication systems.

The schematic diagram of the monolithic CPM laser is shown in Fig. 1(a). A buried-heterostructure (BH) laser is fabricated with a two-step organometallic vapor phase epitaxy (OMVPE) growth technique. First, graded index separate confinement heterostructure (GRIN-SCH) InGaAsP/InGaAs multiquantum well layers[14] are grown on an n^+-InP substrate. Then iron-doped semi-insulating InP is selectively grown around the patterned 2-μm-wide active region to provide electric isolation and reduce parasitic capacitance. Detailed growth procedures and device performance have been reported elsewhere.[14] Standard lithography and wet chemical etching are used to produce the final structure. As shown in Fig. 1(a), the active quantum well region extends throughout the entire cavity to remove undesired waveguide mismatch and to simplify the fabrication process. The uncoated cleaved facets are used as symmetric mirrors. The cavity is divided into five sections: the two end sections near the facets are modulators; the center section is saturable absorber, and the remaining two sections between the modulators and the absorber are active waveguides.

In this monolithic CPM laser an external rf source is used to actively mode lock two counterpropagating pulses



(a)



(b)

FIG. 1. (a) Schematic diagram of the monolithic colliding-pulse mode-locked (CPM) quantum well laser. (b) The microphotograph of the 2.54-mm-long monolithic CPM laser (third laser from the top). The other three lasers are active mode-locked lasers in non-CPM configuration for comparison.

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in the linear cavity. Instead of relying on the two counter-propagating pulses to adjust themselves to collide in the saturable absorber as in the dye lasers,[1] here the two end modulators force the pulses to collide in the center saturable absorber. The transient grating in the saturable absorber produced by these two colliding wave packets stabilizes and shortens the pulses, as demonstrated in the dye lasers. The timing accuracy between the two modulators is then determined by the equal path length of the integrated microstrip transmission lines, which is guaranteed by the lithographic process. The cavity length is 2.54 mm, which corresponds to a round-trip frequency of 16.3 GHz. Both the modulators and the saturable absorber are 70 μm long, and the gaps between sections are 10 μm long. Typical resistance between sections is 2 kΩ. Figure 1(b) shows the microphotograph of the monolithic CPM laser (the third stripe from the top). Also shown in the picture are three active mode-locked lasers in non-CPM configuration for comparison. The fabricated laser has a typical threshold current of 90 mA with the active waveguides biased only. The continuous-wave (cw) lasing wavelength is 1.58 μm.

The small-signal response of the monolithic CPM laser is characterized with an HP 8510 network analyzer up to 20 GHz. Because of the long photon lifetime associated with the long cavity, the direct modulation bandwidth is about 2 GHz. The modulation response decreases monotonically with frequency except in the neighborhood of the cavity resonance of 16.3 GHz, where the response peaks up to about the same level as that at low frequency. The second harmonic of the cavity resonance cannot be seen due to the limited bandwidth of the detector used.

In the mode-locked experiment, 32.6 GHz sinusoidal signals are fed from a low phase-noise synthesizer. This driving frequency is selected to match one-half of the cavity round-trip time. The pulse width, the optical spectrum, and the average output power are monitored simultaneously as the rf frequency is fine tuned for various bias conditions. The pulse width is measured by a noncollinear second-harmonic autocorrelator using a 5-mm-thick $LiNbO_3$ crystal. The spectrum and the power are monitored through an optical fiber butt coupled to the other facet of the laser. The pulse width is sensitive to the changes of the rf frequency, the rf power level, and the dc biases. The optical spectrum gives a direct indication of how well the modes are locked. For example, Fig. 2 shows the spectrum of the CPM laser for various rf power levels at 32.6 GHz. At -25 dBm of rf power (trace 00), there is a dominant single longitudinal mode, similar to that in cw lasing. The spectrum starts to change at $+5$ dBm (trace 06). A significant change occurs at $+10$ dBm (trace 07), where a series of longitudinal modes with peak heights suppressed by more than 10 dB is observed. The spectral width broadens to a couple of nanometers, and the peak lasing wavelength shifts to the longer wavelength side from 1.5812 to 1.5844 μm.

The shortest pulse is obtained when the active waveguide is biased just above threshold (94 mA), with the end modulators and the center saturable absorber tied together through a bias tee. The second-harmonic autocorrelation trace [Fig. 3(a)] exhibits a clean pulse with a full width at half maximum (FWHM) of 2.2 ps. The signal-to-noise ratio is much better than that obtained with the non-CPM active mode-locked lasers on the same laser bar as shown in Fig. 1(b). The autocorrelation data fits well with a hyperbolic secant pulse shape,[11] and the pulse width is 1.4 ps. This is achieved at only 14 dBm of rf power. With additional pulse compression,[2] femtosecond pulses could be obtained. Unlike the mode-locked lasers with external cavities, which suffer from multiple-pulse generation within a single cycle, only a single pulse is observed in this monolithic CPM laser. Figure 3(b) shows the autocorrelation trace over a larger range of time delay. Three pulses are observed at an interval of 30.7 ps, which is one-half of the cavity round-trip time. The dark level, which is measured with the laser turned off, is superimposed on the same trace. Nearly 100% intensity modulation is demonstrated with a peak power of 10 mW. The average optical output power of 0.5 mW is measured from the collimated beam.

The optical spectrum corresponding to the autocorrelator trace of Fig. 3(a) is shown in Fig. 4. From the mea-

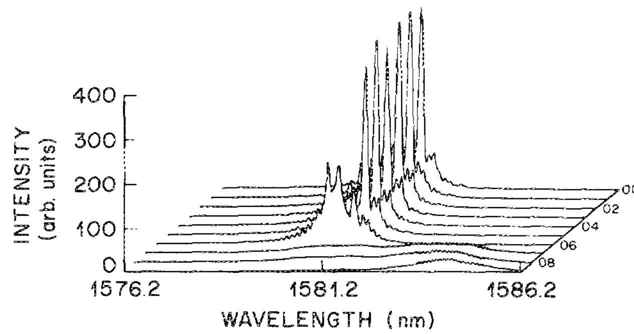

FIG. 2. Optical spectrum of the monolithic CPM laser under various rf power starting at -25 dBm (curve 00) and increasing by steps of 5 dBm. Mode locking is observed at a power level as low as 10 dBm (curve 07).

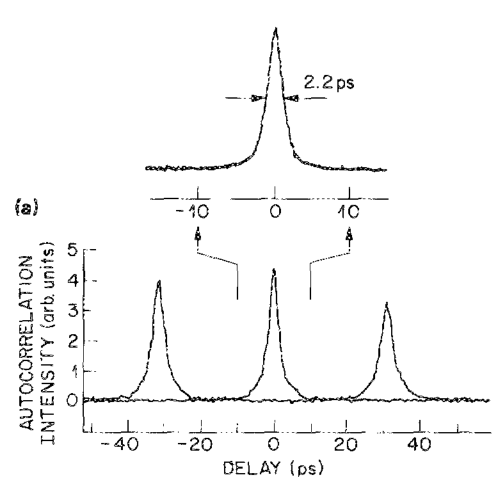

FIG. 3. Second-harmonic autocorrelation trace of the pulses from the monolithic CPM laser. The corresponding pulse width is 1.4 ps, as fitted with a sech^2 pulse shape. (b) Second-harmonic autocorrelation trace of three consecutive pulses. The dark level is superimposed on the trace, showing an optical modulation depth of nearly 100%.

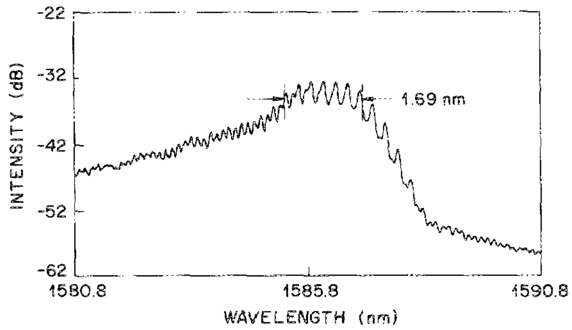

FIG. 4. Optical spectrum of the monolithic CPM laser simultaneously recorded with Fig. 3. The spectral width of 1.69 nm indicates that the 1.4 ps pulse width is transform-limited.

sured spectral width of 1.69 nm, the time-bandwidth product, $(\Delta\tau \cdot \Delta\upsilon)$, is calculated to be 0.3. Thus the 1.4 ps pulse is nearly transform limited. This is the shortest transform-limited pulse ever reported from the monolithic mode-locked semiconductor lasers. The center portion of the spectrum has a mode spacing of 32.6 GHz, while the two sides of the spectrum have a mode spacing of 16.3 GHz. This indicates that the modes around the peak wavelength are tightly locked together. For the non-CPM active mode-locked lasers on the same laser bar [Fig. 1(b)] with comparable pulse width, we are not able to achieve transform-limited time-bandwidth product. Poor mode locking sometimes results in a small sharp pulse riding on a broad pedestal, despite a large $\Delta\nu$ as much as 8 nm.

The monolithic CPM scheme helps to achieve short pulses in the following way: assuming at time zero $(t=0)$ at steady state, two pulses are launched simultaneously from the two end modulators. After one quarter of the round trip time T $(t=T/4)$, the two pulses travel to and collide at the center saturable absorber. The transient grating produced by the interference of the pulses diffracts part of the light pulse back, which adds coherently to the other pulse. This coherent interaction reduces the pulse width in a similar way as in the passive CPM dye lasers. At $t=T/2$, the pulses are resonantly amplified by the modulator at the other facet. Then the pulses collide again at $t=3T/4$. It is interesting to note that during the period of the transient grating, the cavity becomes a coupled-cavity consisting of two subcavities of equal lengths. Such grating coupled cavities limit the bandwidth of the spectrum and help to achieve transformed-limited pulses. It was pointed out in Ref. 1 that the CPM effect is most pronounced when the normalized saturation energy is such that $\beta=2\sigma U_0 \approx 1$, where σ is the absorber cross section and U_0 is the pulse energy per cm^2. Using the exciton absorption cross section of 10^{-13} cm^2 in GaAs/GaAlAs multiquantum wells,[9] and our pulse energy of $U_0 \approx 1.4\times10^{-6}$ J/cm^2, the normalized saturation energy $\beta \approx 2$, which is of the same order of magnitude as the optimum dye lasers.

One of the important factors determining the pulse width of the monolithic CPM semiconductor lasers is the response of the saturable absorber. It has been shown in Ref. 11 that fast saturable absorber contributes substantially to the formation of short pulses. Recently, it was found that the nonlinear light absorption in multiquantum wells at the exciton energy has a very fast relaxation time (300 fs) in addition to the slow recovery time resulting from free-carrier recombination.[9] The fast process is due to the decomposition of excitons, which saturate light absorption very effectively by filling the available exciton states. Thus a very fast saturable absorber can be realized by operating the mode-locked laser at the excitonic transition energy of the quantum wells. Further optimization of the quantum well device structure and the saturation characteristics of the absorber could produce femtosecond pulses without using external pulse compressors.

In summary, we have demonstrated a novel monolithic colliding-pulse mode-locked semiconductor quantum well laser at 1.58 μm. Transform-limited pulses with duration of 1.4 ps at a repetition rate of 32.6 GHz have been obtained, with an intensity modulation depth of nearly 100% and a peak power of 10 mW. These are the shortest transform-limited pulses ever reported for monolithic mode-locked semiconductor lasers.

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